

IN COOPERATION WITH
NEW HAMPSHIRE DEPARTMENT OF TRANSPORTATION

Use of a Ground-Penetrating Radar System to Detect Pre- and Post-Flood Scour at Selected Bridge Sites in New Hampshire, 1996-98

Water-Resources Investigations Report 00-4035



Cover photograph is showing the Peabody River in Gorham, N.H. Mount Washington and the Presidential Range is in the background. (Photograph was taken by J.R. Olimpio, U.S. Geological Survey)

U.S. Department of the Interior
U.S. Geological Survey

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By Joseph R. Olimpio

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Pembroke, New Hampshire
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CONVERSION FACTORS, ABBREVIATIONS, AND SEA LEVEL

	Multiply	By	To obtain
	foot (ft)	0.3048	meter
	mile (mi)	1.609	kilometer
	cubic feet per second (ft ³ /s)	0.02832	cubic meter per second

Sea Level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

ABBREVIATIONS USED IN THIS REPORT

MHz = megahertz

Use of a Ground-Penetrating Radar System to Detect Pre- and Post-Flood Scour at Selected Bridge Sites in New Hampshire, 1996-98

By Joseph R. Olimpio

Abstract

Ground-penetrating radar was used to measure the depth and extent of existing and infilled scour holes and previous scour surfaces at seven bridges in New Hampshire from April 1996 to November 1998. Ground-penetrating-radar survey techniques initially were used by the U.S. Geological Survey to study streambed scour at 30 bridges. Sixteen of the 30 bridges were re-surveyed where floods exceeded a 2-year recurrence interval. A 300-megahertz signal was used in the ground-penetrating radar system that penetrated through depths as great as 20 feet of water and as great as 32 feet of streambed materials.

Existing scour-hole dimensions, infilled thickness, previous scour surfaces, and streambed materials were detected using ground-penetrating radar. Depths to riprap materials and pier footings were identified and verified with bridge plans. Post data-collection-processing techniques were applied to assist in the interpretation of the data, and the processed data were displayed and printed as line plots. Processing included distance normalization, migration, and filtering but processing was kept to a minimum and some interference from multiple reflections was left in the record.

Of the 16 post-flood bridges, 22 ground-penetrating-radar cross sections at 7 bridges were compared and presented in this report. Existing scour holes were detected during 1996 (pre-flood) data collection in nine cross sections where scour depths ranged from 1 to 3 feet. New scour holes were detected during 1998 (post-flood) data

collection in four cross sections where scour depths were as great as 4 feet deep. Infilled scour holes were detected in seven cross sections, where depths of infilling ranged from less than 1 to 4 feet. Depth of infilling by means of steel rod and hammer was difficult to verify in the field because of cobble and boulder streambeds or deep water.

Previous scour surfaces in streambed materials were identified in 15 cross sections and the depths to these surfaces ranged from 1 to 10 feet below the streambed. Riprap materials or pier footings were identified in all cross sections. Calculated record depths generally agree with bridge plans. Pier footings were exposed at two bridges and steel pile was exposed at one bridge. Exposures were verified by field observations.

INTRODUCTION

In 1993, the New Hampshire Department of Transportation (NHDOT) completed scour analysis of 48 bridges across the State that had previously been determined to be scour susceptible. Based on recommended procedures outlined in Richardson and others (1993), 44 of the 48 bridges evaluated had scour estimated to extend below the top of the footings and were classified as "scour critical" (Whitman and Howard, 1992). Additionally, predicted scour was below the elevation of the footings for floods at the 10-year recurrence interval for 35 of the 44 bridges. For New Hampshire bridges that have been in place for 50 years or more, scour-related problems were appreciably less frequent than results from these analyses indicate.

Bridges over waterways that are identified as scour critical require evaluation and monitoring to ensure public safety. However, such evaluation and monitoring measures are costly to apply to large numbers of bridges. Transportation agencies need better information and methods to accurately assess, predict, and remediate scour problems in a cost-effective manner. Detailed field observation of scour processes is needed to achieve these objectives in New Hampshire. Measurements of streambed scour and deposition at bridge sites are essential to studying the scour process; therefore, by understanding this process, better construction techniques and scour countermeasures can be developed to minimize scour effects. Maximum scour at a bridge usually occurs near the peak of a flood when measurements are difficult to collect. Scour holes are often infilled just after the peak flow and during the flow recession. If the scour hole has been infilled, data collected after the flood based on traditional methods (sounding weight) may not be able to detect the maximum scour depth. Pre- and post-flood ground-penetrating-radar (GPR) data collection may be able to detect existing or infilled scour holes that occurred during the flood. GPR techniques are suitable as an alternative to traditional methods of flood-data collection such as the installation of fixed instrumentation or the deployment of mobile flood teams. GPR data collected at bridge sites contain a continuous profile of the streambed and, in some instances, the sub-bed bottom. These sub-bed-bottom reflectors can be correlated to erosional or depositional surfaces, pier footings, previous scour surfaces, or sediment layers (Placzek and others, 1995).

A disadvantage of pre- and post-flood GPR data collection is that it is not a technique used to protect the motorist or the public during a flood and analyses of data may be limited if sufficient hydraulic data are not available to quantify flow velocities during a flood. GPR, however, does provide advantages over other methods in that it can be used to identify historical maximum scour depths, as well as existing or infilled scour holes that occurred during a flood.

In 1995, the U.S. Geological Survey (USGS), in cooperation with the NHDOT, began a study to provide data needed to improve the understanding of bridge-scour processes, scour prediction, and scour monitoring by collecting limited-detail scour data at selected bridges in New Hampshire. As part of this study, GPR was used to measure pre- and post-flood

scour cross-sectional profiles at upstream, downstream, and pier locations at bridge sites. Initially, 30 bridge sites were chosen for pre-flood GPR data collection. Site-selection criteria for GPR data collection were based on (1) physical characteristics of the river and bridge, (2) close proximity of USGS stream-gaging stations to bridge sites, and (3) the occurrence of a flood. The pre-flood GPR data served as a baseline cross-sectional survey for a site. Existing scour, infilling of scour holes, and historical maximum scour surfaces were identified on the records. River-characteristics criteria included the presence of permeable streambed materials that the radar signal was assumed to be able to penetrate. Sites with steep ravines; streambed materials predominantly consisting of large boulders; bedrock channels; large amounts of debris (such as trees, tree stumps, or concrete and granite abutment materials from old bridges); or in saltwater were not chosen for GPR data collection. Close proximity of the bridge to USGS stream-gaging stations also was a selection factor because streamflow could be associated with a recurrence interval. Recurrence interval for floods is defined as the average time interval between occurrences of a flood of a given or greater magnitude, usually expressed in years. When streamflow reached the level of a 2-year or greater recurrence interval based on USGS streamflow data at a nearby gaging station, the bridge was chosen for post-flood GPR data collection.

Purpose and Scope

The purpose of this report is to describe (1) the use of GPR to detect pre- and post-flood scour holes and previous scour surfaces at bridge sites, and (2) the interpretation of data collected from selected bridge sites. This report includes descriptions of the GPR methods and equipment used during this study. Each of the bridge sites are described with interpretations of the geophysical records. Of the original 30 evaluated bridges, 16 bridges with floods exceeding the 2-year recurrence interval were selected for post-flood GPR data collection. Of the 16 bridges surveyed, 11 bridge sites at 7 bridges (fig. 1) were evaluated for pre- to post-flood changes.

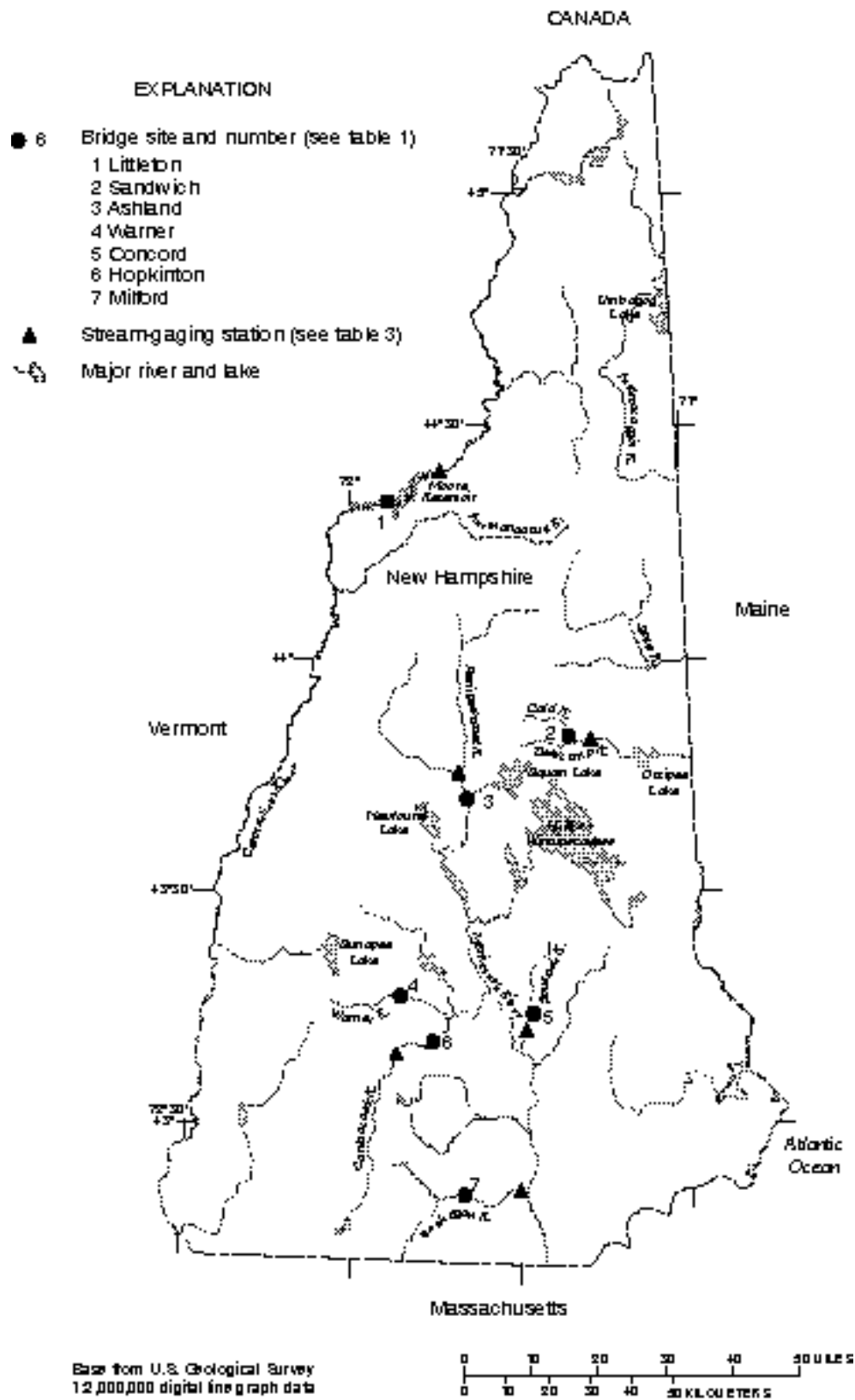


Figure 1. Location of ground-penetrating-radar data-collection sites at seven bridge sites in New Hampshire.

Description of the Study Area

The study area includes bridges crossing the Connecticut, Cold, Pemigewasset, Warner, Soucook, Contoocook, and Souhegan Rivers in northwestern to southern New Hampshire. Selected descriptive characteristics of these bridge sites are shown in table 1.

Use of Terms

In this report, the following terminology is used to describe various bed-bottom-scour characteristics:

Existing scour hole: The bed-bottom scour observed during the 1996 pre-flood cross-sectional data collection. Depth is measured in feet below the streambed reference surface adjacent to the scour hole.

New scour hole: New or deepened scour observed during the 1998 post-flood cross-sectional data collection. Depth is measured in feet below the streambed reference surface adjacent to the scour hole.

Infilling: The partial or complete filling of an existing scour hole observed during the post-flood cross-sectional data collection. Extent of infilling is measured as the difference in hole depths between the pre- and post-flood data collection.

Previous scour surface: Buried scour holes or surfaces that are evident in the GPR record and existed prior to the pre-flood cross-sectional data collection.

Depth is measured in feet below the streambed reference surface at the time the cross section was surveyed.

Multiple: A secondary reflection of the streambed surface in a GPR record that appears below the streambed and is not indicative of sub-bed-bottom reflectors.

Acknowledgments

Information for this study was provided by the NHDOT. The author wishes to thank Dave Powellson, Chief of the Existing Bridge Section of the Bureau of Bridge Design, and his staff, for their cooperation and assistance during this study.

GROUND-PENETRATING RADAR

GPR was used to provide continuous profiles of the streambed surfaces at the seven bridges shown on figure 1. GPR surveys have been used for a variety of subsurface investigations (Beres and Haeni, 1991; Placzek and Haeni, 1995). This investigation used the GPR methods reported by Placzek and Haeni (1995) to obtain profiles of the shallow stratigraphy of subsurface deposits. Depths to reflectors and types of lithologies were verified by comparing depths to reflectors with depths to lithologic units and physical structures on bridge-construction plans.

Table 1. Selected descriptive characteristics of seven bridge sites in New Hampshire

[No., number; NHDOT, New Hampshire Department of Transportation; mi², square mile; ft/ft, foot per foot; ft, foot; NH, New Hampshire; US, United States]

Bridge site No. (fig. 1)	Town	NHDOT No.	Route	River crossed	Drainage area (mi ²)	Slope (ft/ft)	Total width (ft)	Water depth (ft)	Bed-bottom materials
1	Littleton	109/134	NH 18	Connecticut	1,604	0.0005	530	1-20	Silt, fine sand, some boulders
2	Sandwich	238/092	NH 113	Cold	31	.04	146	1-5	Coarse sand, gravel, cobbles
3	Ashland	076/080	US 3 & NH 25	Pemigewasset	634	.001	800	1-8	Medium sand, cobbles
4	Warner	166/103	I-89	Warner	83	.001	191	1-4	Fine to medium sand, gravel, cobbles
5	Concord	160/188	NH 9	Soucook	77	.004	178	1-4	Fine to medium sand, boulders
6	Hopkinton	049/096	NH 9 & US 202	Contoocook	400	.0006	312	1-12	Fine to medium sand, some boulders
7	Milford	123/133	NH 13	Souhegan	120	.001	112	1-8	Fine to medium sand, some boulders

The GPR-survey system transmits radio-frequency electromagnetic pulses into the water and bed-bottom sediments and receives energy reflected back from surface and subsurface reflectors. Reflectors can be any subsurface contact between water and geologic materials or geologic materials with different physical and electrical properties, such as the interface between lithologic units or layers within a unit. Manmade materials such as concrete and steel also can be a subsurface reflector. The surveys were conducted with a 300-MHz-center-frequency monostatic transmitting and receiving antenna that was near the water surface. The profiles can be examined visually to locate below water and subsurface features. Interpretations of GPR profiles are improved by comparison with lithologic logs and bridge-construction plans.

Beres and Haeni (1991) provide an interpretation guide for various types of reflector patterns for unconsolidated deposits. Sections of the GPR profiles with parallel reflectors can indicate the presence of laminated fine-grained sediments, such as pond-bottom sediments observed in this study. Complex, subparallel, and chaotic GPR-profile patterns generally indicate coarse-grained sediments. Inverted V-shaped patterns are indicative of point reflectors that could be from cobbles or boulders.

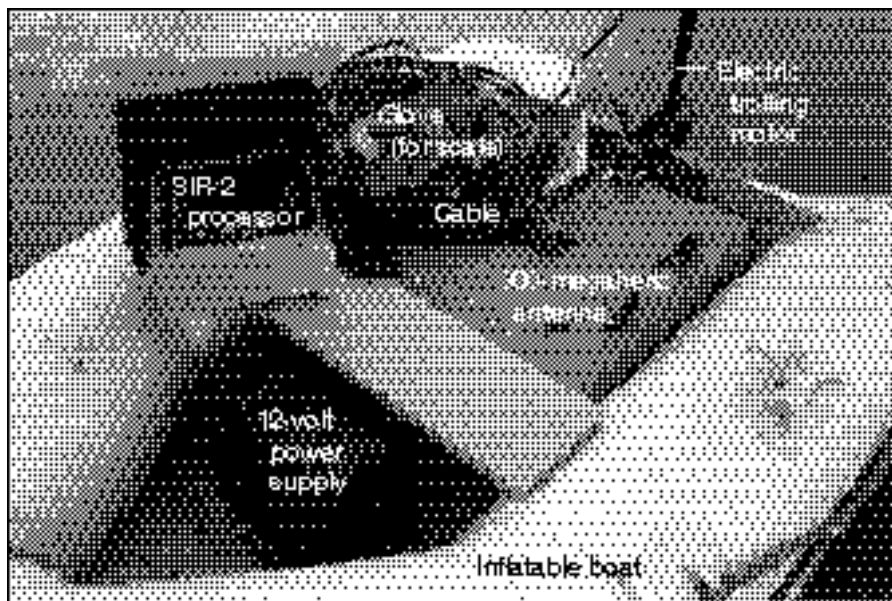
All reported depths to existing and new scour holes and bed-bottom and sub-bed-bottom reflectors are approximate. These depths are based upon estimated ground-penetrating radar two-way travel times for water, saturated sands, till, and bedrock (table 2).

Table 2. Approximate ground-penetrating radar two-way travel times for selected materials

Material	Approximate two-way travel times, in nanoseconds per foot
Water	18
Saturated sands	10
Tills	6.5
Bedrock	5

Equipment

A Subsurface Interface Radar System-2 (SIR-2) manufactured by Geophysical Survey Systems, Inc. was used to investigate scour in this study. Data are displayed in real-time on a color display and stored on an internal hard drive. For this study, the GPR processor and 300-MHz antenna were placed in a small inflatable boat (fig. 2). The inflatable boat



(Photograph by J.R. Olimpio, U.S. Geological Survey)

Figure 2. Ground-penetrating radar data-collection equipment.

provides a stable platform that has minimal effect on radar-signal transmission and reception. In deep water (depth is greater than or equal to 4 ft), the operator sat in the boat, which was propelled across the water surface by an electric trolling motor. In shallow water (depth is less than 4 ft), the equipment operator waded alongside the boat and pushed the boat by hand in water or dragged it across sand, gravel, and cobble bars. These methods of equipment deployment were fast, safe, and easily transportable from the vehicle to the river's edge by one person. A geophysical record was collected at one bridge per day.

Data-collection Methods

Cross-sectional GPR profiles were collected at upstream and downstream bridge faces, from the left bank to the right bank of the river, directly beneath the leading and trailing edges of the bridge, and within 1 ft of each pier nose. (Left bank and right bank terminology used here is from a facing downstream perspective). Profiles also were collected 1 ft from and alongside the piers parallel with the axis of the river, from downstream to upstream within about 20 to 40 ft downstream of the nose of the pier, alongside the length of the pier, and within about 20 to 40 ft upstream of the nose of the pier.

Depths of scour holes, exposed pier footings, channels, boulders, and streambeds were measured with a surveying rod during data collection. Attempts to probe into the streambed with a steel rod to verify depths of infilled holes were met with limited success, as the presence of cobbles and boulders or deep water usually prevented verification. The water-surface elevation was measured from a known reference point on the bridge before and after data were collected.

Transmission velocities of the radar signal were used to interpret depth to a reflector. Approximate GPR two-way travel times for selected materials (Geophysical Survey Systems, Inc., 1994) used for interpretation are summarized in table 2.

GPR data were processed to enhance reflector patterns in the data. Distance normalization, migration, and signal amplification were used selectively to process the data. These processes, as performed using commercial computer software, are described by Geophysical Survey Systems, Inc. (1995). Processing was kept to a minimum to preserve as much of the original record as possible.

SCOUR ESTIMATES AT BRIDGE SITES

The results of the geophysical surveys presented in this section include selected GPR cross sections, showing pre- and post-flood-scour data at seven bridges. Baseline GPR data were collected at 30 bridge sites as part of the pre-flood data-collection effort. The criteria for post-flood data collection at bridge sites were the occurrence of a 2-year or greater recurrence interval flood at any of the 30 bridge sites during the study. The flood-recurrence interval was determined from USGS streamflow data at gaging stations located either on each river near the bridge, or compared to USGS streamflow data at gaging stations that were about 2 to 10 mi away on an adjacent river with similar basin characteristics. Flood-flow data at stream-gaging stations near bridges in New Hampshire are presented in table 3. Bridges that had uninterpretable GPR data from the pre-flood survey also were eliminated as potential post-flood GPR data-collection sites. Thus, 22 pre- and post-flood GPR cross sections (11 pre-flood sections and 11 post-flood sections) at 7 bridge sites were used for this study. Water-surface elevations were determined by using a steel tape and known reference mark on the bridge deck. The vertical distance from the reference point to the water surface was measured twice during each site visit. This measured distance from the reference point to the water surface was used to obtain a water-surface elevation for each day GPR data were collected (elevation data for the reference point were obtained from NHDOT bridge plans). The water-surface elevation was used as a point of reference on the GPR cross sections. Estimated two-way travel times (in nanoseconds per foot, table 2) in water, saturated sand, till, and bedrock were used to determine depths to the surface of the streambed, existing and new scour holes, infilled streambed sections, and subsurface reflectors such as previous scour surfaces, pier footings, and riprap materials. Depths to reflectors were calculated based on the known water-surface elevation and travel time through the water or subsurface materials. These calculated depths were compared to cross-sectional data on NHDOT bridge plans to verify depths to features such as streambed and top-of-footing and(or) bottom-of-footing.

The footing outline is superimposed on the GPR records. Footing placement on the record is based on known dimensions of the footing, the top and bottom elevations of the footing, and the two-way travel time of the radar signal in the bed-bottom materials (footing data are from NHDOT bridge plans).

Table 3. Flood-flow data at stream-gaging stations near seven bridges in New Hampshire

[Bridge site distance is distance in miles from bridge to gaging station. NHDOT reference no., New Hampshire Department of Transportation bridge reference number; GPR, Ground-penetrating Radar; ft³/s, cubic feet per second; >, greater than]

Stream-gaging station information: river, location, station identifier	Bridge site, river, distance, NHDOT reference no.	1996 Pre-flood GPR data collection: Date and flow (ft ³ /s)	1998 Post-flood GPR data collection: Date and flow (ft ³ /s)	Highest flow during study: Date and flow (ft ³ /s)	Approximate recurrence interval (years)
Soucook River Concord 01089100	Route 9 Soucook 1.9 160/188	5/20/96 311	11/05/98 17	3/10/98 1,890	5-10
Connecticut River Dalton 01131500	Route 18 Connecticut 11.2 109/134	8/08/96 1,123	11/10/98 1,500	4/01/98 42,000	25-50
Bearcamp River Tamworth 01064801	Route 13 Cold 10 238/092	8/12/97 15	11/13/98 129	6/14/98 6,150	>50
Contoocook River Henniker 01085000	Route 9/202 Contoocook 4.2 049/096	12/04/96 3,430	11/06/98 179	6/18/98 5,740	2-5
Pemigewasset Plymouth 01076500	Route 3/25 Pemigewasset 5.9 076/080	10/03/96 237	11/16/98 1,640	6/14/98 22,200	2-5
Souhegan River Merrimack: 01094000	Route 13 Souhegan 3.8 123/133	8/11/96 54	11/20/98 76	10/22/96 6,260	5-10
Contoocook River Henniker 01085000	I-89 Warner 8.5 166/103-4	12/04/96 3,430	11/06/98 179	6/18/98 5,740	2-5

Scour holes and depths to exposed bridge features (top-of-footing, top-of-steel pile) were manually measured during GPR data collection using a surveying rod. These measurements also were used to verify depths to these features, when identified, in the GPR cross sections. A summary of scour estimates at each of the 7 bridges and 22 cross sections is provided in table 4. A detailed description for each bridge site follows this summary.

Route 9 Bridge

A bridge is located on Route 9 and crosses the Soucook River (about 100 ft wide). The bridge is 178 ft long by 44 ft wide, and is supported by two 6-column-bridge pile bents. Each of the columns are 3 ft wide and 5 ft long. Each 6-column-bridge pile bent is 40 ft long.

Pre- and post-flood GPR data were collected at the upstream and downstream bridge faces and along

Table 4. Ground-penetrating-radar scour data for seven bridges in New Hampshire

[No., number]

Site	Section of river and figure No.	Ground-penetrating radar survey dates	Existing scour hole depth observed during study period, in feet, and location	New scour hole depth observed during study period, in feet, and location	Maximum discharge observed during study period, in cubic feet per second, and date	Infilling observed during period, in feet, and location	Previous streambed surface depth below bed bottom, in feet, and location
Route 9 over Soucook River in Concord							
Concord, Route 9 over Soucook River	Downstream cross-section (fig. 3)	8/13/96	1.3 Right bank pier	1.7 Right bank pier	1,890 3/10/98	0.5 Left bank pier	1-4 Left and right sides of section
		11/5/98					
Concord, Route 9 over Soucook River	Pier-set cross-section (fig. 4)	8/13/96	2.8 Column 5	2.0 Column 2	1,890 3/10/98	None	1-5 Between columns
		11/5/98					
Route 18 over Connecticut River in Littleton							
Littleton, Route 18 over Connecticut River	Upstream cross-section (fig. 5)	8/26/96	2.5 Pier 2	None	42,000 4/1/98	2.0 Pier 2	None
		11/10/98					
Route 13 over Cold River in Sandwich							
Sandwich, Route 13 over Cold River	Upstream cross-section (fig. 6)	8/12/97	None	3.0 Pier	6,150 ¹ 6/14/98	None	6-13 Middle of river channel
		11/13/98					
Sandwich, Route 13 over the Cold River	Downstream cross-section (fig. 7)	8/12/97	None	1.2 Pier	6,150 ¹ 6/14/98	None	6-9 Middle of river channel
		11/13/98					
Routes 202 and 9 over Contoocook River in Hopkinton							
Hopkinton, Routes 202 and 9 over Contoocook River	Upstream cross-section (fig. 8)	12/4/96	2.0 Right bank pier	None	5,740 ² 6/18/98	2.0 Right bank pier	None
		11/6/98					
Interstate I-89 southbound over Warner River in Warner							
Warner, I-89 southbound over Warner River	Upstream cross-section (fig. 9)	12/3/96	1.2 Middle of river channel	None	5,740 ² 6/18/98	0.7 Middle of river channel	1-8 Middle of river channel
		11/6/98					
Interstate I-89 northbound over Warner River in Warner							
Warner, I-89 northbound over Warner River	Downstream cross-section (fig. 10)	12/3/96	1.0 Right bank pier	None	5,740 6/18/98	1.0 Right bank pier	4 Middle of river channel
		11/6/98					

Table 4. Ground-penetrating-radar scour data for seven bridges in New Hampshire—Continued

[No., number]

Site	Section of river and figure No.	Ground-penetrating radar survey dates	Existing scour hole depth observed during study period, in feet, and location	New scour hole depth observed during study period, in feet, and location	Maximum discharge observed during study period, in cubic feet per second, and date	Infilling observed during period, in feet, and location	Previous streambed surface depth below bed bottom, in feet, and location
Routes 3 and 25 over Pemigewasset River in Ashland							
Ashland, Routes 3 and 25 over Pemigewasset River	Upstream cross-section (fig. 11)	10/3/96 11/16/98	3.0/1.0 Left channel/pier	3.5/2.0 Left channel/pier	22,200 6/14/98	2.0 Middle of river channel	6-8 Middle of river channel
Route 13 over Souhegan River in Milford							
Milford, Route 13 over Souhegan River	Downstream cross-section (fig. 12)	8/11/96 11/20/98	2.0 Right bank pier	3.0 Right bank pier	6,260 10/22/96	None	2-3 Left bank pier
Milford, Route 13 over Souhegan River	Right bank pier cross-section (fig. 13)	8/11/96 11/20/98	3.0/2.0 us pier/ds pier	4.0/4.0 us pier/ds pier	6,260 10/22/96	4.0 ds pier	None

¹Maximum discharge for the Bearcamp River, Tamworth, 4.2 miles east of this site was 6,150 cubic feet per second on June 14, 1998.

²Maximum discharge for the Contoocook River, Henniker, 9.6 miles south of this site was 5,740 cubic feet per second on June 18, 1998.

the right and left bank sides of the pile bents. The downstream bridge face and the right-bank pier cross sections were interpretable with GPR and were used for comparison of pre- and post-flood conditions. Water depths range from 1 to 5 ft during the study. The streambed materials at this site consist of fine-to-coarse sand with cobbles. Radar-signal-penetration depths ranged from 5 ft in water to 13.5 ft in streambed sediments.

A stream-gaging station (01089100, table 3) is on the Soucook River 1.9 mi south of the bridge. Pre-flood GPR data were collected on May 20, 1996, (streamflow of 311 ft³/s, table 3) and post-flood GPR data were collected on November 5, 1998, (streamflow of 17 ft³/s, table 3). The highest flood flow during this time interval was 1,890 ft³/s and was recorded on March 10, 1998. This flow corresponds to a 5- to 10-year flood.

Downstream Bridge-face Cross Section

The 1996 (pre-flood) cross section (fig. 3A) shows an undulating streambed of strong sand reflectors. Near the left-bank column a small existing scour hole measures about 1 ft deep. An existing scour hole (1.3 ft deep) is adjacent to the right-bank column. Previous scour surfaces (thin faint reflectors in the middle left and middle right of the section) are 1 to 2.5 ft below the streambed. Depth to the top of the column footing in this cross section is 7 ft below the streambed.

The 1998 (post-flood) cross section (fig. 3B) shows a gradual smoothing of the streambed and infilling of the small existing scour hole near the left-bank column. This infilling measures 0.5 ft deep. The existing scour hole identified in the pre-flood section adjacent to the right-bank column now measures 1.7 ft deep. The previous scour surface near the right-bank column is easily identified in this section as a discontinuous thin subparallel reflector on the left and right sides of the record, and is 1.8 to 3.7 ft below the present streambed. The scour surface near the left-bank column may represent the potential maximum extent of scour that occurred during the intervening period (between pre- and post-flood measurements). The inverted triangular reflectors near the right-bank column are interference patterns from the concrete column. Depth to the top of the column footing in this cross section remains unchanged at about 7 ft.

Column-set Cross Section, Upstream to Downstream

The 1996 (pre-flood) cross section (fig. 4A) shows a strong sand reflector representing the streambed, across the entire record, in shallow water. This shallow reflector dips downward, from left to right, toward the downstream end of the record, ending at an existing scour hole at column 5. The hole depth is 2.4 ft. The inverted triangular reflectors just to the left of column 2, and to the right of the scour hole at column 5, represent reflections off of exposed steel-pile sections. Previous scour surfaces (thin faint reflectors beneath the hole in the middle right of the record) range from 1.6 to 4.8 ft beneath the streambed. Riprap protection of the pier footing is represented by a strong, thick, parallel-wavy reflector on the right side of the record above the footing. The position of this reflector on the record agrees with measured elevation data from the bridge plans. Average depth to the top of the pier footing is about 10 ft.

The 1998 (post-flood) cross section (fig. 4B) shows the same strong sand reflector representing the streambed, from left to right across the entire record, but there is a new scour hole 1.2 ft deep and 4 ft wide located around column 2. The inverted triangular reflectors are still present near columns 2 and 5. The shallow streambed reflector follows the same downward trend toward the pre-existing scour hole at column 5. The hole at column 5 (2.4 ft deep) appears to have remained relatively stable. There is no evidence of infilling in the record (fig. 4B). The riprap protection above the pier footing is still represented in the record, but the thick parallel-wavy reflector pattern is more obscured in this record by thick wavy reflectors just above it. Average depth to the top of the footing remains the same at 10 ft.

Route 18 Bridge

The Route 18 bridge in Littleton crosses the 450-ft-wide Connecticut River and is supported by four piers. Each pier is 6.5 ft wide and 31 ft long. Pre- and post-flood GPR data were collected at the upstream and downstream bridge faces and along both the right and left bank sides of each pier (fig. 5). The upstream bridge face cross section was used for comparison of pre- and post-flood conditions. Water depths ranged from 2 to 32 ft during the study. The streambed materials at this site consist of silt,

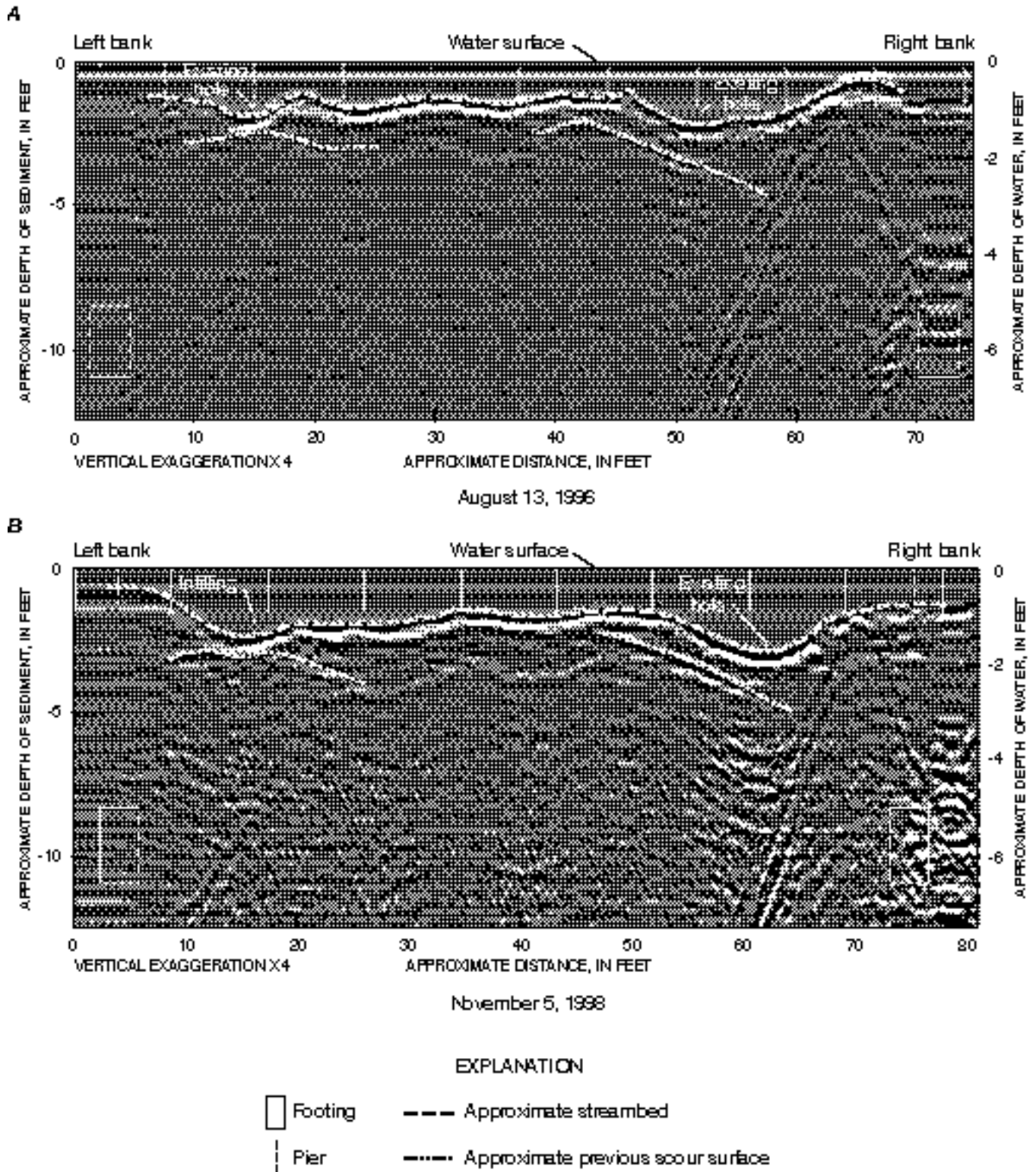


Figure 3. Ground-penetrating-radar profiles of the downstream bridge-face cross sections for (A) 1996 pre-flood and (B) 1998 post-flood data collection, from left to right bank, Route 9 over the Soucook River, Concord, N.H.

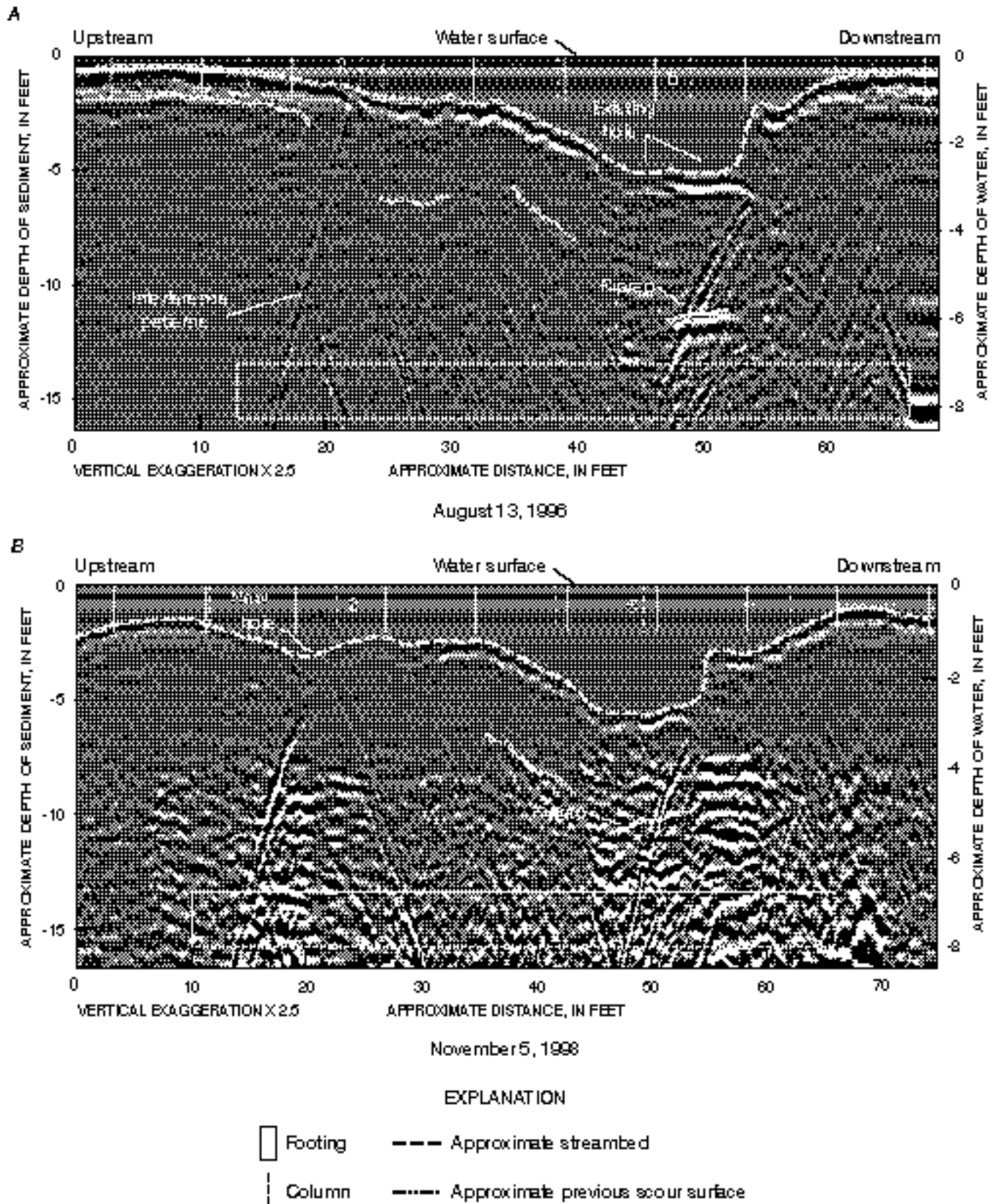


Figure 4. Ground-penetrating-radar profiles of the pier-set cross sections for (A) 1996 pre-flood and (B) 1998 post-flood data collection, from upstream to downstream, Route 9 over the Soucook River, Concord, N.H.

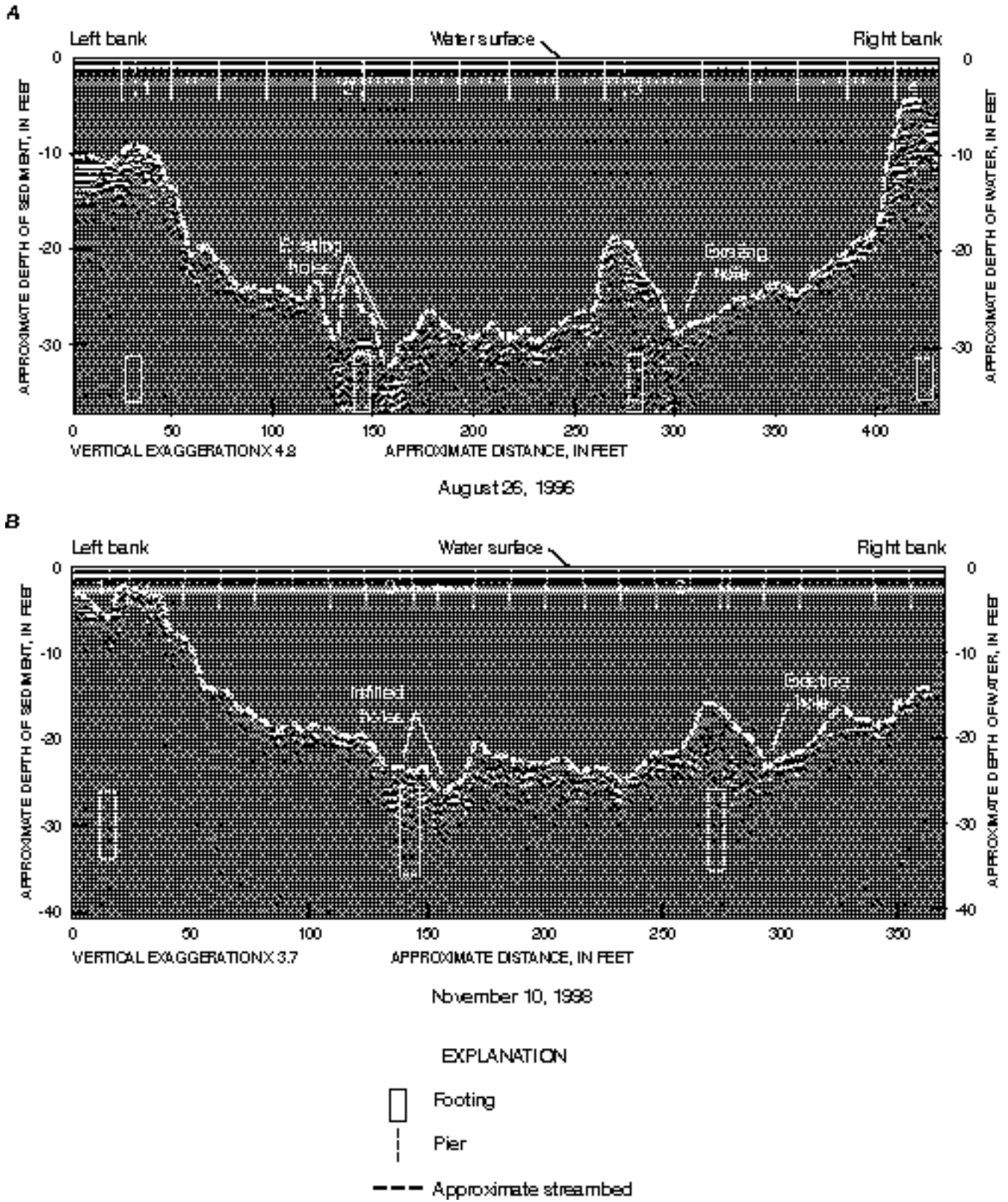


Figure 5. Ground-penetrating-radar profiles of the upstream bridge-face cross sections for (A) 1996 pre-flood and (B) 1998 post-flood data collection, from left to right bank, Route 18 over the Connecticut River, Littleton, N.H.

fine-to-medium sand, and some boulders (New Hampshire Department of Transportation, 1992). Radar-signal-penetration depths were about 32 ft in water and 8.2 ft in streambed materials.

A stream-gaging station (01131500, table 3) is on the Connecticut River 10 mi north of the bridge. Pre-flood GPR data were collected on August 8, 1996, and the flow at the gaging station was 1,123 ft³/s. Post-flood GPR data were collected on November 10, 1998, and the flow at the gaging station was 1,500 ft³/s. The highest flood flow during this time interval was 42,000 ft³/s recorded on April 1, 1998. This flow corresponds to a 25- to 50-year flood.

The 1996 (pre-flood) cross-section (fig. 5A) data were collected in water up to 32 ft deep. The GPR signal is attenuated by the water and only able to penetrate about 8.2 ft of the streambed sediments. At each pier, as seen on the record, a mound of streambed material represents the granite riprap protection that was installed to prevent streambed scour. At pier 2, 2.5-ft-deep scour holes exist on both sides of the pier (fig. 5A). A small hole (2.3 ft deep) developed to the right of pier 3.

The 1998 (post-flood) cross section (fig. 5B) was collected in water somewhat shallower than in 1996 (23 ft deep). The GPR signal is still attenuated (but to a lesser degree because the water is shallower) and is able to penetrate further into the streambed sediments. At pier 2, the hole configuration has changed; the scour holes have filled in (about 2 ft deep), but the overall depth of streambed material over the top of the footing is less (this result may represent the settlement of riprap as streambed material is scoured away from the toe of the riprap slope). At pier 3, the mound of riprap is still identifiable on the record, and the hole to the right of the pier appears to have filled in with 1.2 ft of material. Previous scour surfaces were not identified because the radar signal was attenuated by the depth of the water and the fine-grained streambed materials.

Route 13 Bridge

The Route 13 bridge in Sandwich crosses the Cold River and is 146 ft long by 32 ft wide, and has 2 bridge spans. The river width is about 40 ft. The single pier is 3.5 ft wide and 40 ft long.

Pre- and post-flood GPR data were collected at the upstream and downstream bridge faces and along

the right and left bank sides of the pier. The upstream and downstream cross sections were used for comparison of pre- and post-flood conditions. Observed water depths ranged from 1 to 4.2 ft during the study. The streambed materials at this site consist of coarse sand, gravel, cobbles, and boulders. Radar-signal-penetration depths were about 4.2 ft in water and 11 ft in streambed materials.

A stream-gaging station (01064801, table 3) is on the Bearcamp River 4.2 mi east of the bridge. Pre-flood GPR data were collected on August 12, 1997, and the flow at the gaging station was 15 ft³/s. Post-flood GPR data were collected on November 13, 1998, and the flow at the gaging station was 129 ft³/s. The highest flood flow for this time period was 6,150 ft³/s and was recorded on June 14, 1998. This corresponds to a greater than 50- to 100-year flood.

Upstream Bridge-face Cross Section

The 1997 (pre-flood) cross-section data (fig. 6A) were collected in shallow water from 0 to 2.5 ft deep. The section represents the right half of the bridge opening from the pier to the right bank. The radar signal did not penetrate the dry sand and cobble streambed materials in the left bridge-face opening. The streambed appears as a thick continuous reflector (in the top middle of the record) that trends downward to the deepest part of the streambed at an existing depression 2.2 ft deep. This bridge site restricts the flow of water during flood flows. This restriction causes contraction scour to occur (the 2.2-ft-deep depression in the center of the channel). No scour holes were observed during this survey. However, thin wavy reflectors represent previous scour surfaces of unknown age about 8 ft below the streambed (fig. 6A). The entire right half of the record shows chaotic wavy thin reflectors. This is a cobble-boulder section of the streambed.

The 1998 (post-flood) cross-section data (fig. 6B) were collected in deeper water (up to 4.4 ft deep) than in 1997. Similar to the upstream record in figure 6A, data for the entire bridge opening were collected but only the data for the right bridge face opening are shown for comparison to the 1997 data. A scour hole about 2 ft deep exists in front of the pier. The depth to the top of the pier footing is about 2 ft below the streambed. Beneath this hole, parallel strong reflectors represent the top of the pier footing. Large boulders (riprap) to the right of the pier are

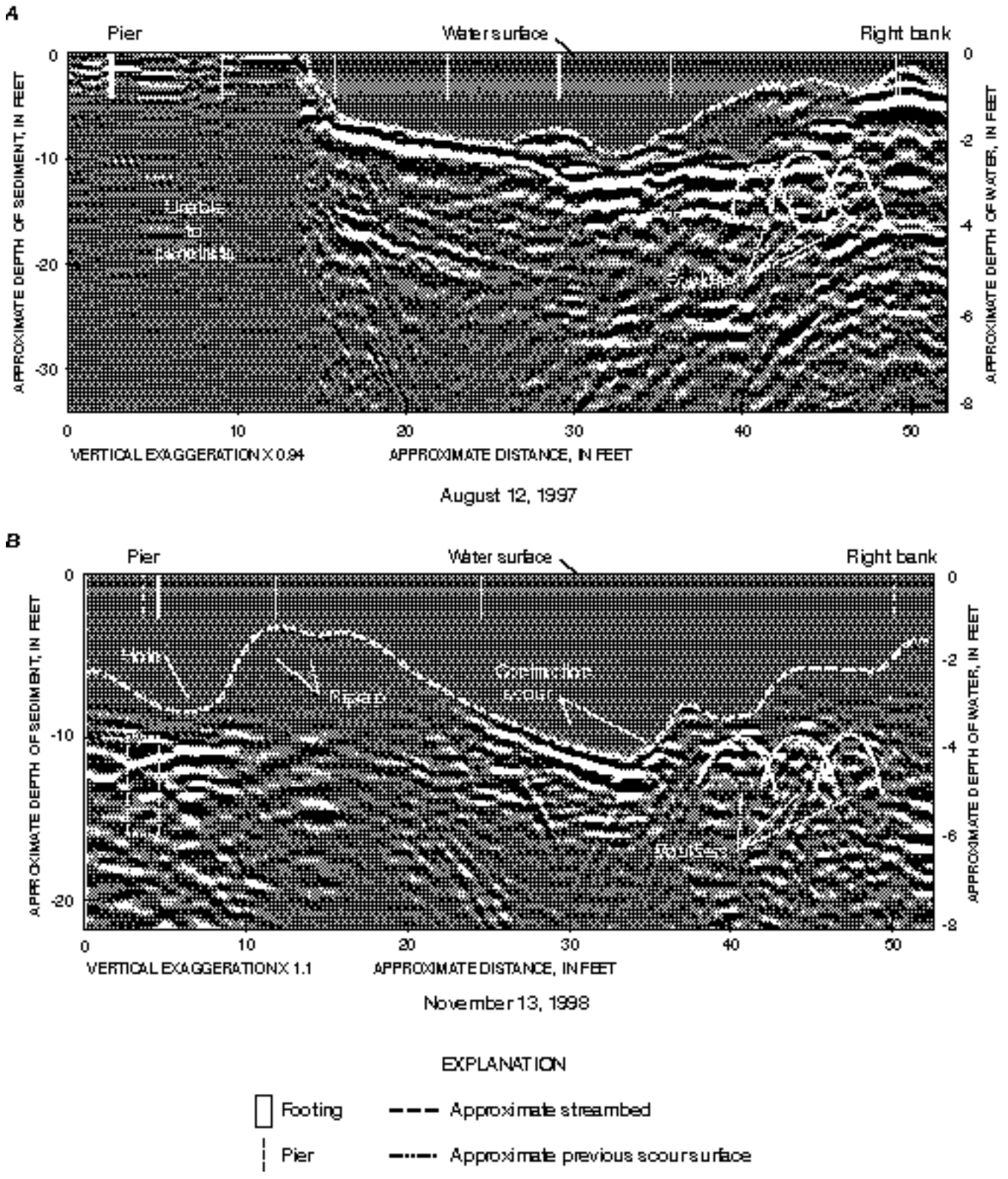


Figure 6. Ground-penetrating-radar profiles of the upstream bridge-face cross sections for (A) 1997 pre-flood and (B) 1998 post-flood data collection, from pier to right bank, Route 13 over the Cold River, Sandwich, N.H.

represented by a mound of faint chaotic reflectors. The depression in the middle of the channel is 0.6 ft deeper than the depression in the 1997 record. This depression could be the result of continued contraction scour processes occurring during flood flows. Previous scour surfaces apparent in the 1997 data (fig. 6) are less readily identifiable; they are obscured by the interfering inverted triangular reflection signature of boulders on the streambed. The right half of the record is similar to the 1997 record; chaotic wavy reflectors are the dominant signature. Streambed-bottom materials on this side of the bridge opening appear to be protected from scour processes by large boulders.

Downstream Bridge-face Cross Section

The 1997 (pre-flood) cross-section data (fig. 7A) were collected in water from 0 to 2 ft deep. The section represents the right half of the bridge opening from the pier to the right bank. The radar signal did not penetrate the dry sand and cobble streambed materials in the left bridge-face opening. The streambed appears as a thick continuous reflector on the left side of the record trending downward to the right. No scour holes were observed in this survey, however, thin wavy reflectors represent previous scour surfaces that are about 6 to 9 ft below the streambed and up to 2 ft below the bottom of the footing. On the right side, cobbles, boulders, and a coarse sand streambed produce chaotic and thin wavy reflection patterns. There is approximately 7 ft of streambed material above the footing.

The 1998 (post-flood) cross-section data (fig. 7B) were collected in water up to about 3 ft deep. Similar to the upstream record (fig. 6), data for the entire bridge opening were collected but only the data for the right bridge-face opening are shown for comparison to the 1997 data. The thick, continuous reflector sloping toward the right (shown in the 1997 data), is replaced in 1998 by a discontinuous flat-lying reflector (streambed materials have been removed and boulders have moved into the section). A new scour hole has formed (1.2 ft deep) to the right of the pier. Interference patterns from cobbles and boulders (inverted triangles) fill much of the record; field observations confirm the movement of sand out of the section and movement of riprap protection material from the upstream bridge-face area to the downstream bridge-face area during a recent flood. Thin wavy

reflectors representing previous scour surfaces are still present at about 6 to 9 ft below the streambed. There is 6 ft of streambed material above the footing; this result indicates that 1 ft of material has been removed from the downstream nose of the pier.

Routes 202 and 9 Bridge

The Routes 202 and 9 bridge in Hopkinton that crosses the Contoocook River is 312 ft long by 60 ft wide, and has 2 piers. The river is approximately 180 ft wide, and each pier is 5 ft wide and 70 ft long.

Pre- and post-flood GPR data were collected at the upstream and downstream bridge faces and along the right and left bank sides of both piers. The upstream bridge-face cross section was used for comparison of pre- and post-flood conditions. Observed water depths ranged from 4 to 13 ft during the study. The streambed materials at this site consist of medium-grained sand (New Hampshire Department of Transportation, 1992). Radar-signal-penetration depths were 13 ft in water and 4 ft in streambed materials.

A stream-gaging station (01085000, table 3) is on the Contoocook River 5.9 mi west of the bridge. Pre-flood GPR data were collected on December 4, 1996, and the flow at the gaging station was 3,430 ft³/s. Post-flood GPR data were collected on November 6, 1998, and the flow at the gaging station was 179 ft³/s. The highest flood flow for this time period was 5,740 ft³/s and was recorded on June 18, 1998. This flood flow corresponds to a 2 to 5-year flood.

The 1996 (pre-flood) cross-section data (fig. 8A) were collected in 2 to 13 ft of water. The streambed is represented by a continuous thick wavy reflector. Below the streambed, thin subparallel discontinuous reflectors represent layering of fine-grained sediments (silt or sand) and inverted triangular interference patterns represent coarse-grained materials (cobbles or boulders). At the left bank pier, there is 2.5 ft of streambed material above the top of the pier footing. An existing 2-ft-deep scour hole is at the front-left side of the right bank pier.

The 1998 (post-flood) cross section (fig. 8B) shows a bed-bottom geometry similar to the 1996 data. However, 0.75 ft of infilling has occurred at the left-bank pier and there is now 2 ft of infilled material above the right-bank pier footing. The thin subparallel

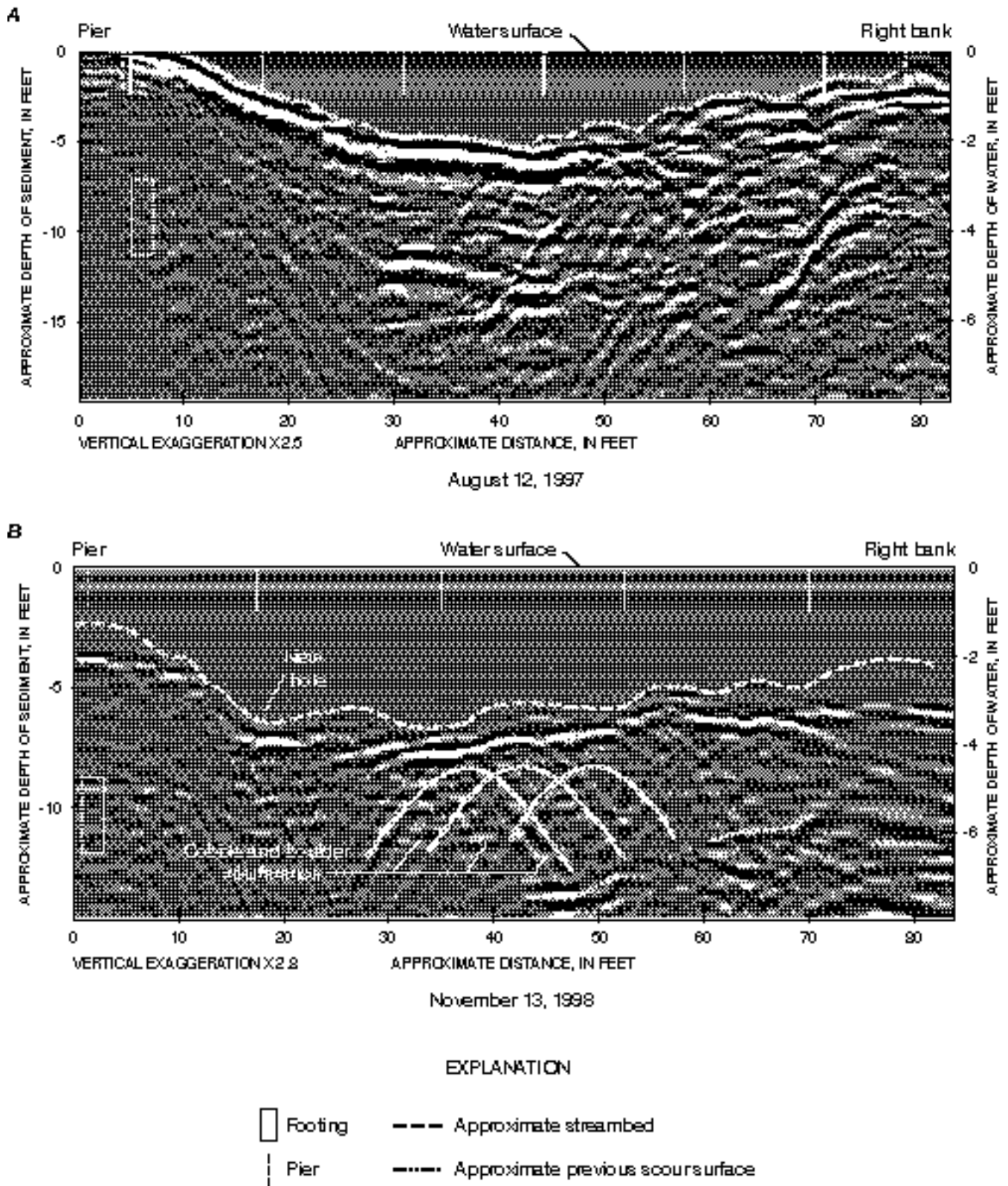


Figure 7. Ground-penetrating-radar profiles of the downstream bridge-face cross sections for (A) 1997 pre-flood and (B) 1998 post-flood data collection, from pier to right bank, Route 13 over the Cold River, Sandwich, N.H.

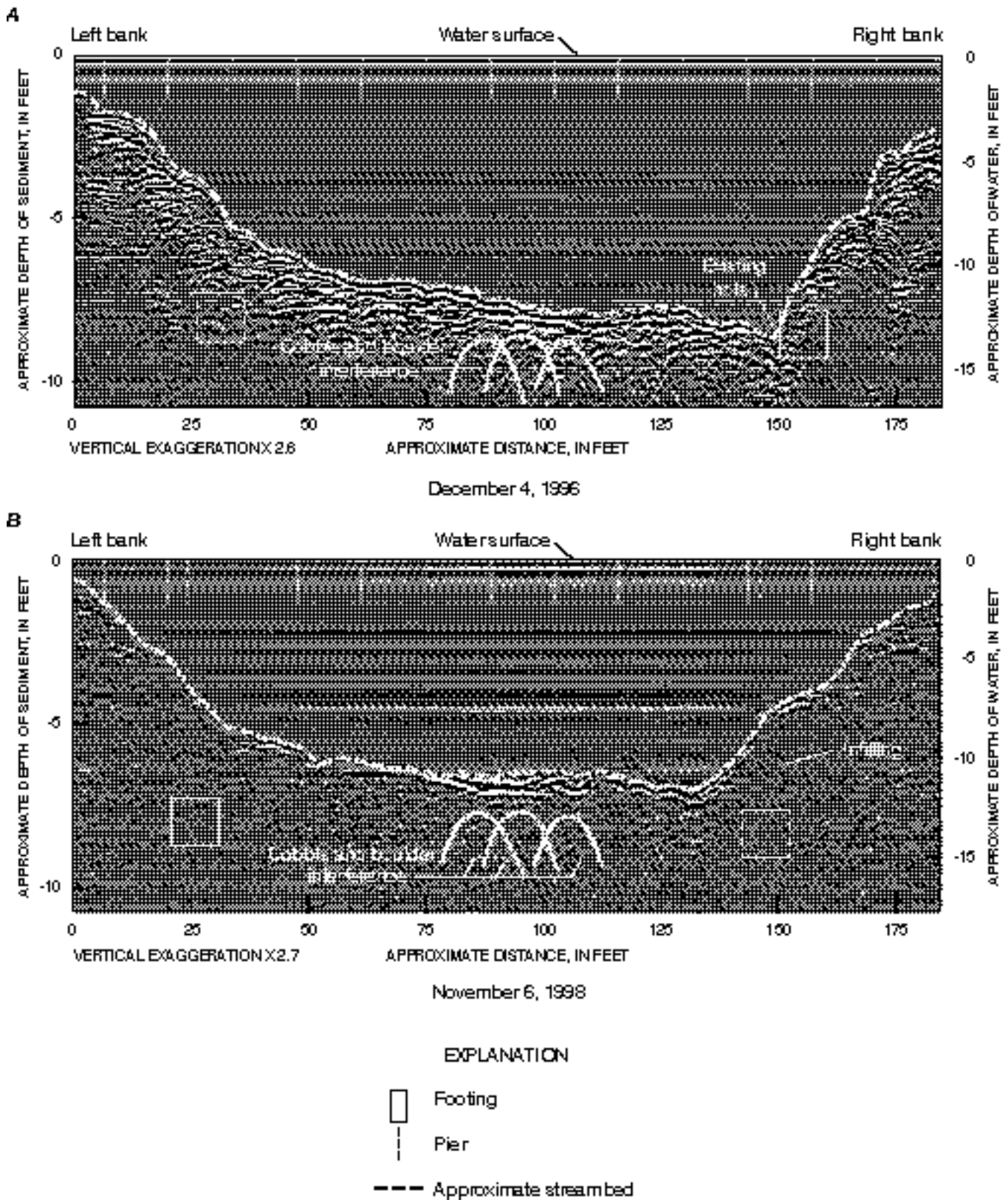


Figure 8. Ground-penetrating-radar profiles of the upstream bridge-face cross sections for (A) 1996 pre-flood and (B) 1998 post-flood data collection, from left to right bank, Routes 202 and 9 over the Contoocook River, Hopkinton, N.H.

reflectors beneath the streambed in the center of the record are not as distinct as the 1996 data; they are obscured somewhat by the inverted triangular signature of the cobble-boulder sublayer. No previous scour surfaces were observed in either the pre- or post-flood surveys at this bridge.

Interstate 89 Southbound Bridge

The Interstate 89 Southbound bridge in Warner crosses the 90-ft-wide Warner River, is 190 ft long by 52 ft wide, and has 2 piers. Each pier is 3 ft wide and 68 ft long.

Pre- and post-flood GPR data were collected at the upstream and downstream bridge faces and along both the right and left bank sides of the two piers. The upstream bridge-face cross section was used for comparison of pre- and post-flood conditions. Observed water depths ranged from 2 to 10 ft during the study. The streambed materials at this site consist of sand and gravel. Radar-signal-penetration depths ranged from 6 ft in water and 20 ft in streambed materials.

A stream-gaging station (01085000, table 3) is on the Contoocook River 9.6 mi south of the bridge. This gaging station was used as an indicator for potential flood-flows on the Warner River (fig. 1). Even though the gage is not on the Warner River, the flows are similar. Pre-flood GPR data were collected on December 4, 1996, and the flow at the Contoocook River gaging station was 3,430 ft³/s. A comparison of drainage areas (Davidian, 1984) provided an estimate of 1,268 ft³/s at the Warner River site. Post-flood GPR data were collected on November 6, 1998, and the flow at the Contoocook River gaging station was 179 ft³/s. The estimated discharge at the Warner River site was 66 ft³/s. The highest flood flow for the Contoocook River in Henniker during this time interval was 5,740 ft³/s and was recorded on June 18, 1998. This result corresponds to a 2- to 5-year flood.

The 1996 (pre-flood) cross section (fig. 9A) shows a thin wavy streambed reflector extending across the entire record. An existing 1.2 ft scour hole is in the middle of the river channel. A thin wavy subparallel reflector extends across the middle center of the record and represents a multiple reflection of the streambed. Previous scour surfaces of sand or sand and gravel appear as thin subparallel sloping reflectors

in the center of the record at 1 to 3 ft below the streambed. Thin dense wavy reflectors 9 ft below the streambed at the left bank pier represent the top of the riprap protection for the left-bank pier footing.

The 1998 (post-flood) cross section (fig. 9B) shows a similar thin parallel streambed reflector across the entire record but the streambed is now a smooth surface. Approximately 0.7 ft of material infilled the middle of the river channel. A thin subparallel reflector extends across the top-middle of the record and represents a similar multiple to that shown in the 1996 record. Previous scour surfaces of sand or sand and gravel appear as discontinuous thin wavy reflectors (obscured somewhat by multiple reflectors of the streambed) 7.5 ft below the streambed. These scour surfaces may represent the potential maximum extent of scour that occurred during the 23 months between measurements.

Interstate 89 Northbound Bridge

The Interstate 89 Northbound bridge in Warner crosses the 90-ft-wide Warner River, is 190 ft long by 52 ft wide, and has 2 piers. Each pier is 3 ft wide and 68 ft long.

Pre- and post-flood GPR data were collected at the upstream and downstream bridge faces and along the right and left bank sides of the two piers. The downstream bridge-face cross section was used for comparison of pre- and post-flood conditions. Observed water depths ranged from 2 to 10 ft during the study. The streambed materials at this site consist of sand and gravel. Radar-signal-penetration depths were as great as 10 ft in water and 20 ft in streambed materials.

A stream-gaging station (01085000, table 3) is on the Contoocook River 9.6 mi south of the bridge. This gaging station was used as an indicator for potential flood-flow events on the Warner River even though the gage is not on the Warner River. Pre-flood GPR data were collected on December 4, 1996, with a flow rate of 3,430 ft³/s. The highest flow of 5,740 ft³/s was recorded on June 18, 1998. This flow corresponds to a 2- to 5-year flood.

The 1996 (pre-flood) cross section (fig. 10A) shows a thin wavy streambed reflector extending across the entire record. A small existing scour hole (1 ft deep) is on the left side of the right pier. A thin wavy parallel reflector extends across the middle

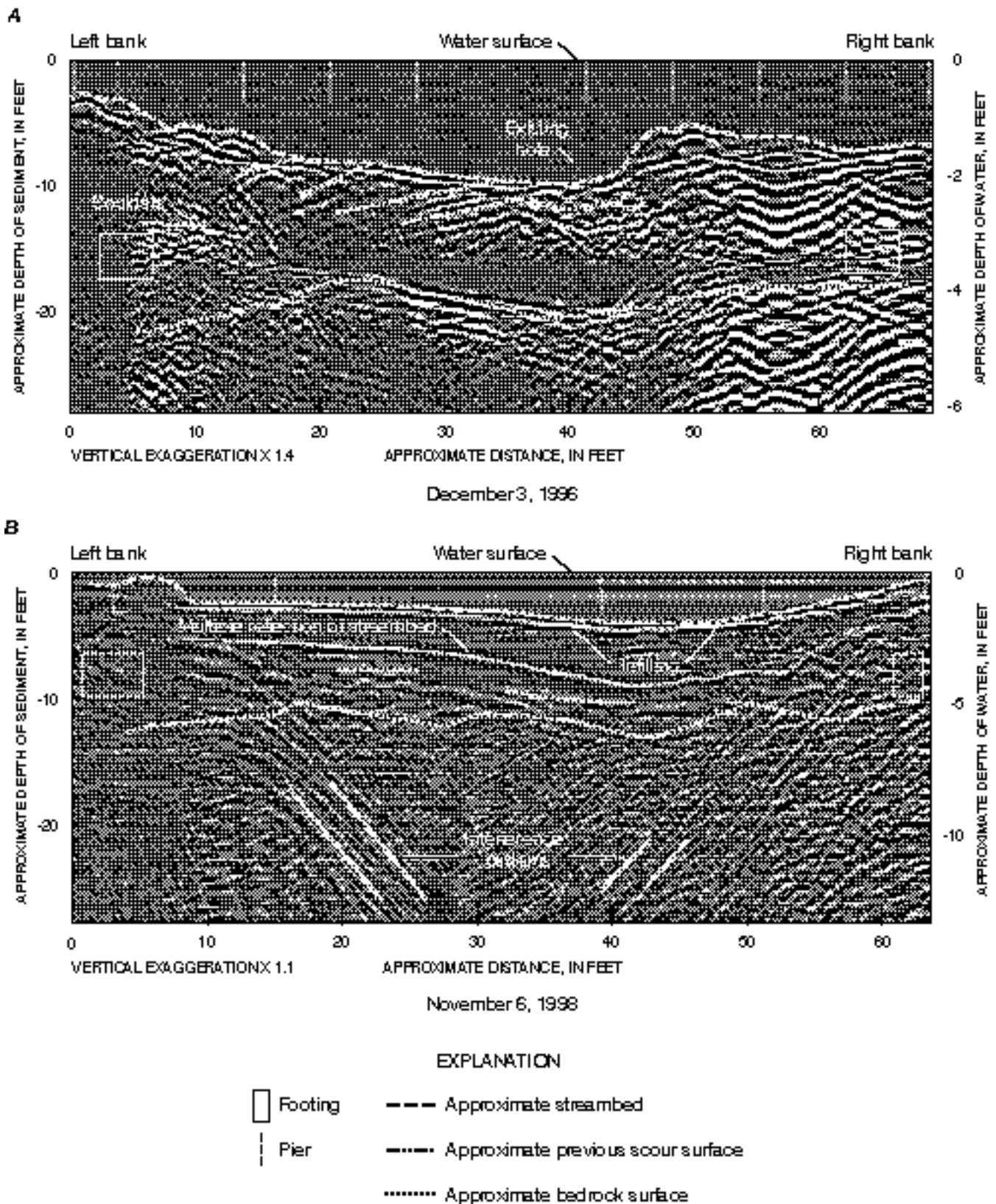


Figure 9. Ground-penetrating-radar profiles of the upstream bridge-face cross sections for (A) 1996 pre-flood and (B) 1998 post-flood data collection, from left to right bank, Interstate 89 southbound over the Warner River, Warner, N.H.

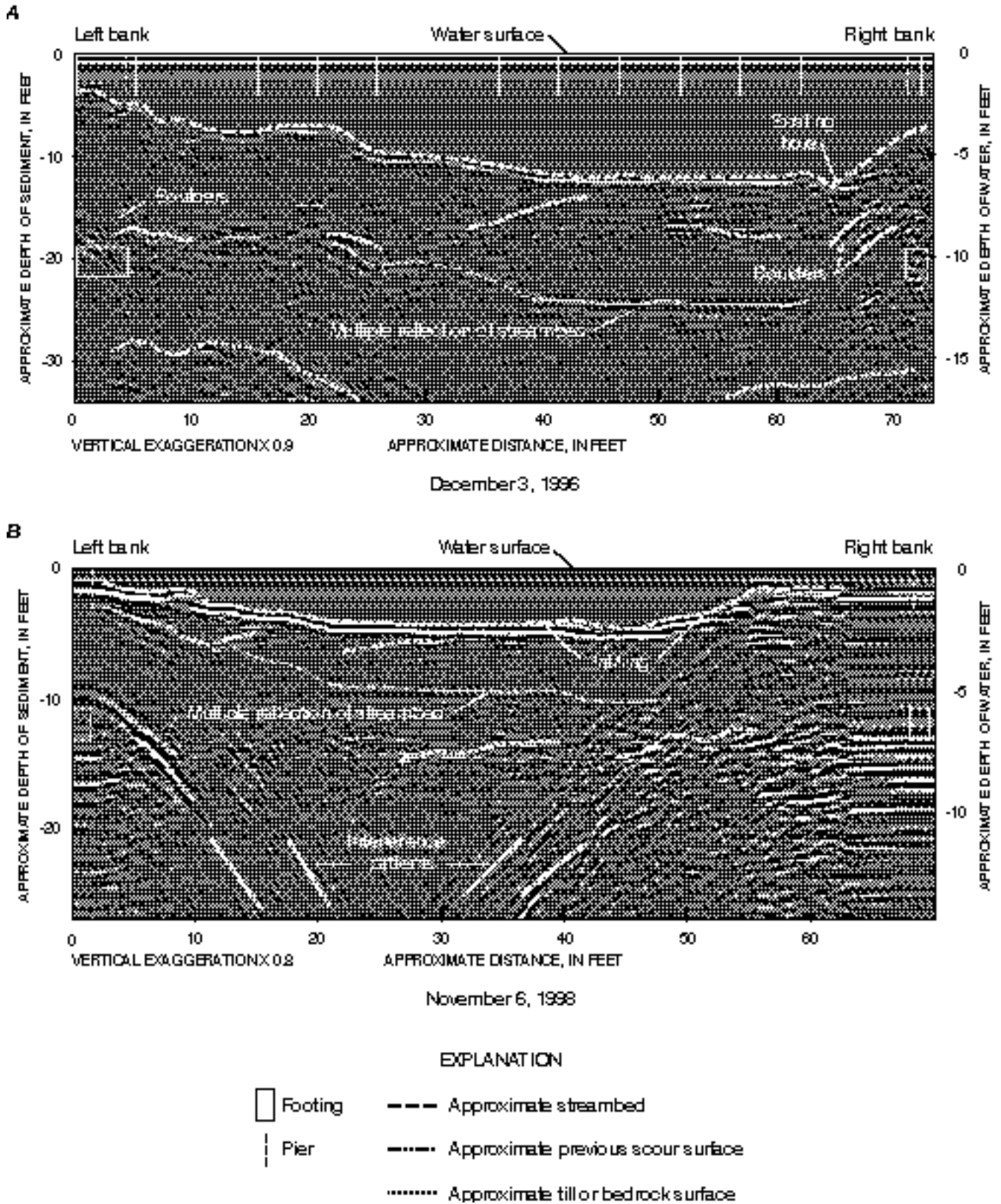


Figure 10. Ground-penetrating-radar profiles of the downstream bridge-face cross sections for (A) 1996 pre-flood and (B) 1998 post-flood data collection, from left to right bank, Interstate 89 northbound over the Warner River, Warner, N.H.

center of the record 11.3 ft below the streambed and represents a multiple reflection of the streambed. Previous scour surfaces of sand or sand and gravel appear as multiple thin wavy reflectors at 3.8 ft below the streambed across the entire record. Boulder protection of the pier footing is identified on the record as chaotic wavy reflectors at both piers 11 ft below the streambed.

The 1998 (post-flood) cross section (fig. 10B) shows the same thin wavy streambed reflector present in the 1996 record extending across the entire record. The thin wavy parallel reflector extending across the middle center of the record represents the same multiple reflection of the streambed. Previous scour surfaces of sand or sand and gravel appear as similar multiple thin wavy reflectors at between 2 and 10 ft below the streambed. The deepest scour surfaces could potentially represent the potential maximum extent of scour that occurred during the intervening period between measurements. There are only subtle changes in the streambed; a flat streambed at left-center changes to a cobble-boulder streambed on the right side of the record, and the small existing scour hole identified in the pre-flood section has been infilled with 1 ft of streambed material.

Routes 3 and 25 Bridge

The Routes 3 and 25 bridge in Ashland crosses the Pemigewasset River and is 800 ft long, 24 ft wide, and has 6 piers. The flood plain is 500 ft wide. Only one of the 6 piers is in the 300-ft-wide river. This 1 pier is 8 ft wide and 32 ft long.

Pre- and post-flood GPR data were collected at the upstream and downstream bridge faces and along the right and left bank sides of the pier. The upstream bridge-face cross section was used for comparison of pre- and post-flood conditions. Observed water depths during the study ranged from less than 1 to 6 ft. The streambed materials at this site consist of fine-to-medium sand and cobbles. Radar-signal-penetration depths were as great as 6 ft in water and 7 ft in streambed materials.

A stream-gaging station (01076500, table 3) is 3.8 mi north of the bridge. Pre-flood GPR data were collected on October 3, 1996, and the flow at the gaging station was 237 ft³/s. Post-flood GPR data were collected on November 16, 1998, and the flow at the gaging station was 1,640 ft³/s. The highest flood

flow for this time period was 22,200 ft³/s and was recorded on June 14, 1998. This flow corresponds to a 2- to 5-year flood.

The 1996 (pre-flood) cross-section (fig. 11A) data were collected in water 0 to 3 ft deep. An 18 ft-wide area around the center pier consisted of a sand and gravel bar (less than 0.5 ft water depth) and is represented by the flat dark low-frequency band at the top-center of the record. Field observations of streambed features (ripples, elongated scour channels, sand bars) indicate that the streambed consisting of sands and gravels is mobile at this bridge site. The streambed is represented by the thick subparallel reflector that forms a 3-ft-deep hole in the middle of the channel on the left side of the pier and a 2-ft-deep hole in the middle of the channel on the right side of the pier. A 1-ft-deep scour hole exposes a steel pile on the left side of the pier. Infilling of sands and gravels (2 ft thick) is represented by the highly reflective wavy bands in both river bed channels.

The 1998 (post-flood) cross-section (fig. 11B) data were collected in water 1-5 ft deep. (The sand and gravel bar around the center pier is now submerged under 1 ft of water). The streambed is represented by the same subparallel reflector identified in the 1996 record (fig. 11A). A 6-ft-deep depression exists in the river channel left of center in the record. Contraction scour may be occurring between the pier and the left bank and the scour depression may be the result of this contraction. A new 3-ft-deep scour hole exposes the steel pile on the left side of the pier. This scour hole is 2 ft deeper than the hole identified in the 1996 data. The wavy chaotic streambed reflectors to the right of the pier represent an infilling of sand and gravel about 2 ft thick. Previous scour surfaces exist below the infilled material on the right side of the record and may represent the potential maximum extent of scour that occurred during the intervening period between measurements.

Route 13 Bridge

The Route 13 bridge in Milford crosses the Souhegan River and is 112 ft long and 50 ft wide. This bridge has one concrete and stone pier that is 10 ft wide and 60 ft long. The river width is about 100 ft.

Pre- and post-flood GPR data were collected at the upstream and downstream bridge faces and along the right and left bank sides of the pier. The

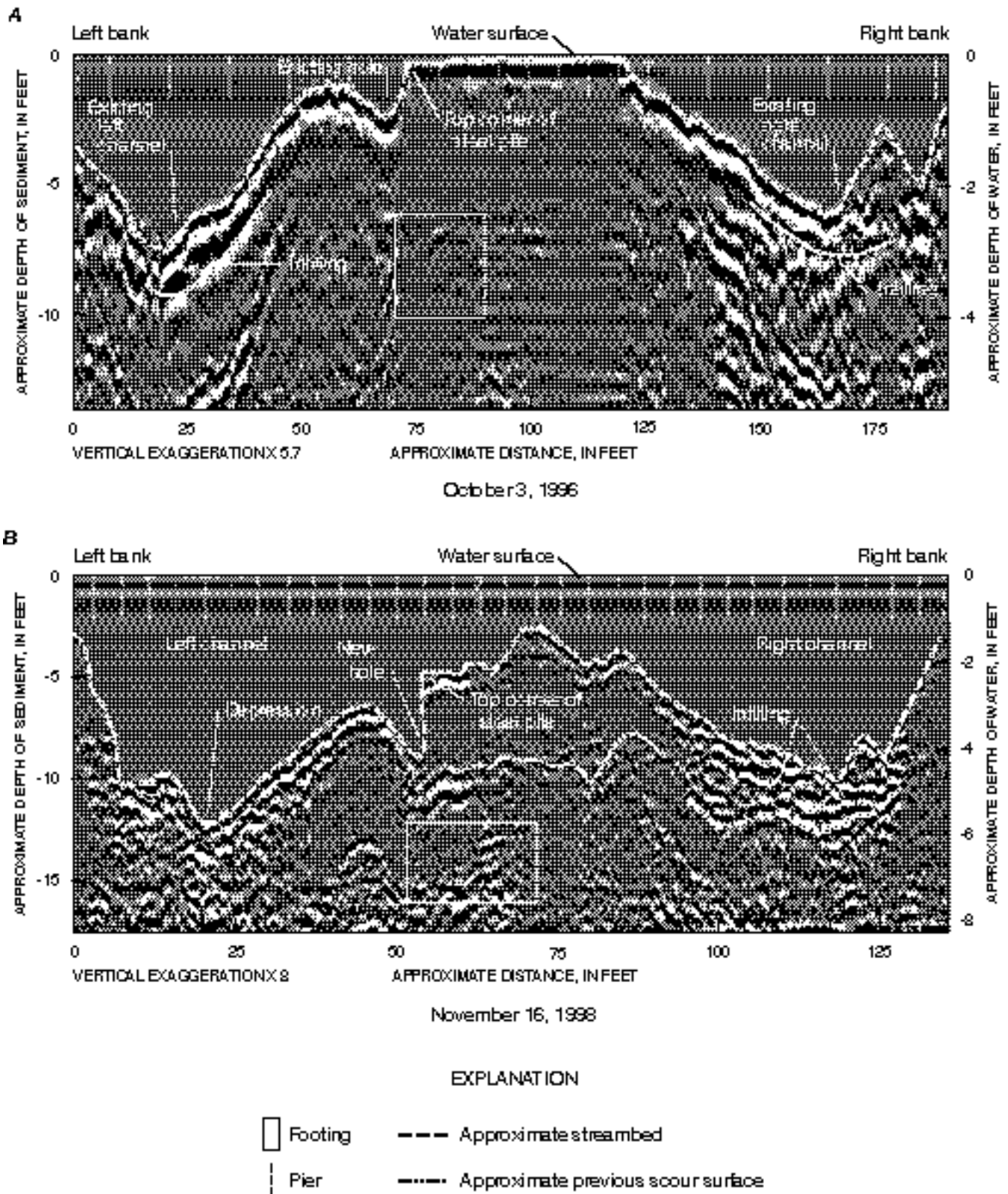


Figure 11. Ground-penetrating-radar profiles of the upstream bridge-face cross sections for (A) 1996 pre-flood and (B) 1998 post-flood data collection, from left to right bank, Routes 3 and 25 over the Pemigewasset River, Ashland, N.H.

downstream bridge-face cross section and the right bank side-pier cross section were used for comparison of pre- and post-flood conditions. Observed water depths ranged from 1 to 8 ft during the study. The streambed materials at this site consist of silt, fine-to-medium sand, and some boulders. Radar-signal-penetration depths were about 8 ft in water and about 6 ft in streambed materials.

A stream-gaging station (01094000, table 3) is 8.5 mi east of the bridge. Pre-flood GPR data were collected on August 11, 1996, and the flow at the gaging station was 54 ft³/s. Post-flood GPR data were collected on November 20, 1998, and the flow at the gaging station was 76 ft³/s. The highest flood flow for this time period was 6,260 ft³/s and was recorded on October 22, 1996. This flow corresponds to a 5- to 10-year flood.

Downstream Bridge-face Cross Section

The 1996 (pre-flood) cross section (fig. 12A) shows an irregular streambed represented by a thin parallel reflector. A 5-ft-deep channel exists on the left side of the record. Chaotic inverted triangular reflectors dominate the right side of the record and are evidence of boulders in the streambed. A previous scour surface on the left side of the pier is represented by a thin diagonal reflector 0 to 4 ft below the streambed and is overlain by more recent infilled sand of the current streambed. A small existing 2-ft-deep scour hole is to the right of the pier.

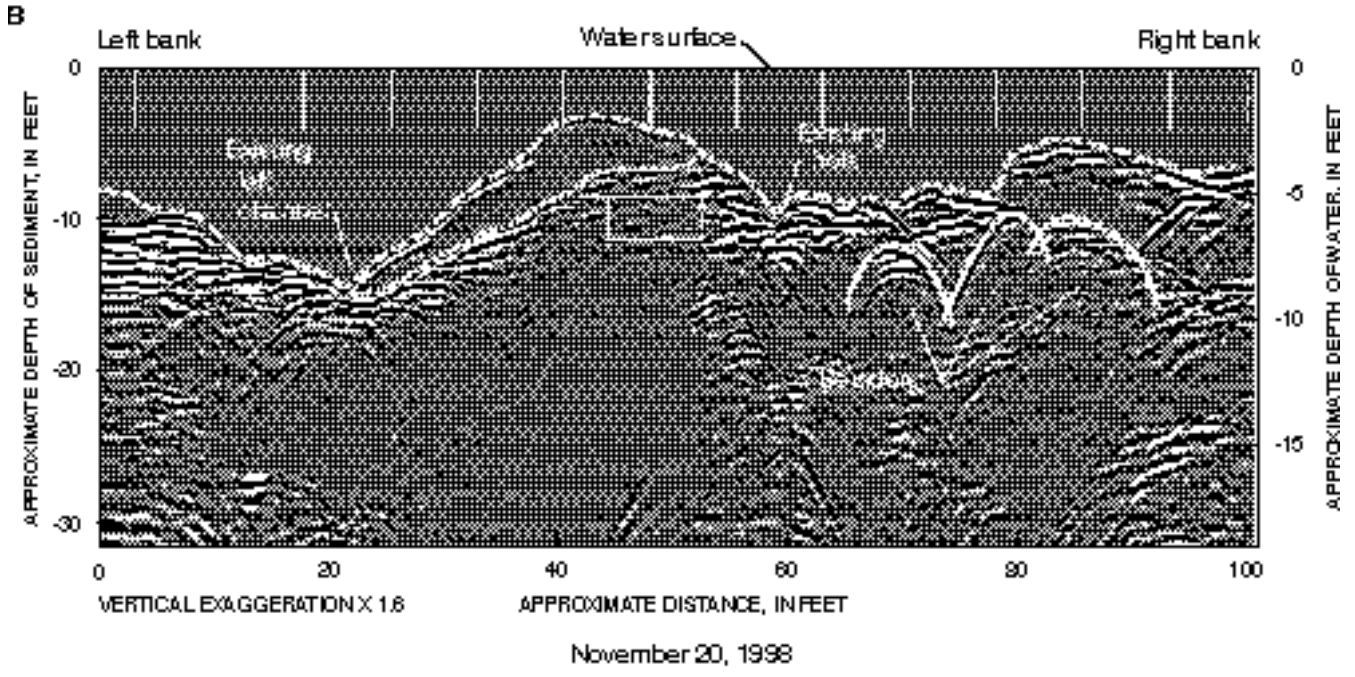
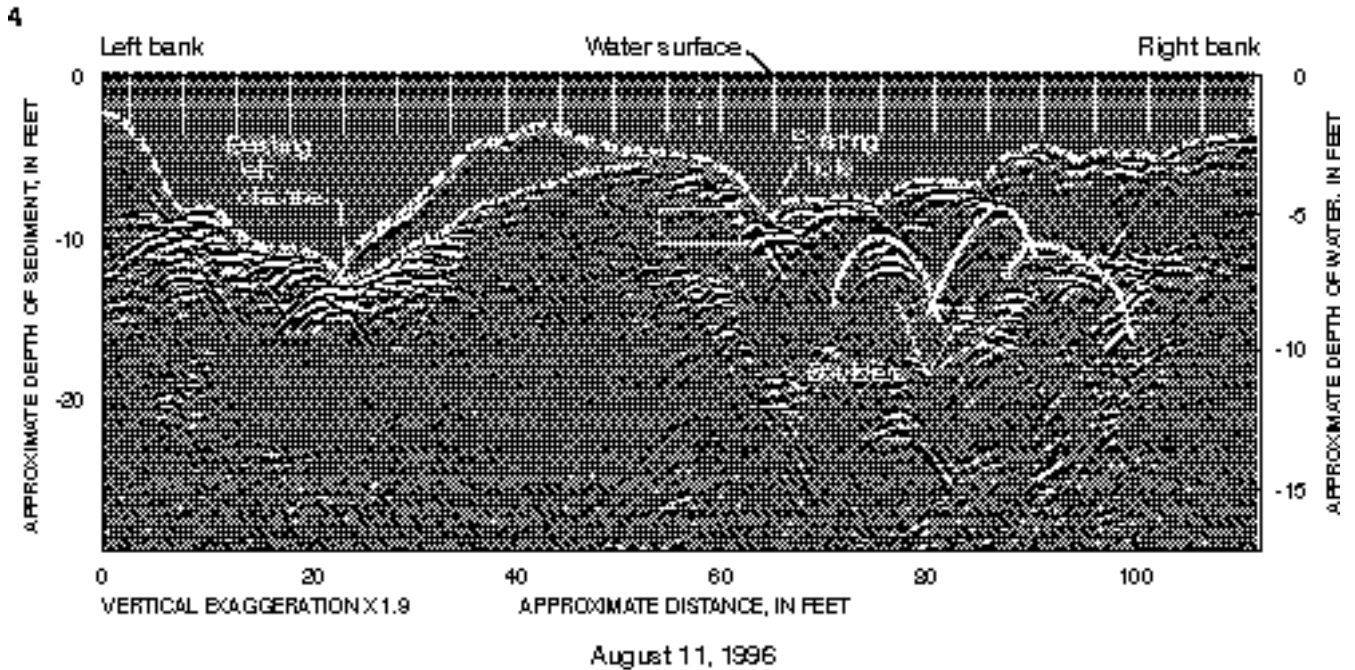
The 1998 (post-flood) cross section (fig. 12B) is similar to the 1996 record with some differences. On the left side of the record, the scour channel is 1.5 ft below the bottom of the footing and almost 1 ft deeper than the 1996 scour channel, indicating that sand was scoured out of the section. The previous scour surface in the top center of the record is still identifiable and

the sand-bed material above this surface to the left of the pier has shifted slightly to the right accumulating over the pier footing. This scour surface may represent the potential maximum extent of scour that occurred during the intervening period between measurements. The small existing scour hole to the right of the pier and the chaotic reflector signature of the streambed boulders on the right side of the record remain unchanged.

Right-bank-pier Cross Section

The 1996 (pre-flood) cross section (fig. 13A) shows an irregular streambed represented by thin wavy parallel reflectors. An existing 3-ft-deep scour hole (hole 1) is at the upstream center section of the footing. Inverted triangular reflectors dominate the center of the record and represent interference patterns from boulders present in the streambed. Two existing scour holes in the streambed (holes 2 and 3) are 1 and 2 ft deep, respectively, and are at the downstream center section of the footing. A strong subparallel reflector is across the bottom third of the record and represents a multiple reflection of the streambed. Radar-signal penetration in streambed sediments is blocked by the presence of boulders in the streambed.

The 1998 (post-flood) cross section (fig. 13B) shows a similar irregular streambed represented by thin wavy parallel reflectors. An additional 1 ft of scour has occurred at hole 1 identified in the 1996 section (left-center at the footing upstream end) and extends downward slightly past the top of the pier footing. The extent of the two existing scour holes at the downstream center section of the footing also have changed. Existing scour hole 2 is now 4 ft deep (2 ft deeper than in 1996) and hole 3 has been infilled. A previous scour surface now exists at hole 3 and is overlain by 4 ft of new streambed materials.



EXPLANATION





-  Footing
-  Approximate streambed
-  Pier
-  Approximate previous scours surface

Figure 12. Ground-penetrating-radar profiles of the downstream bridge-face cross sections for (A) 1996 pre-flood and (B) 1998 post-flood data collection, from left to right bank, Route 13 over the Souhegan River, Milford, N.H.

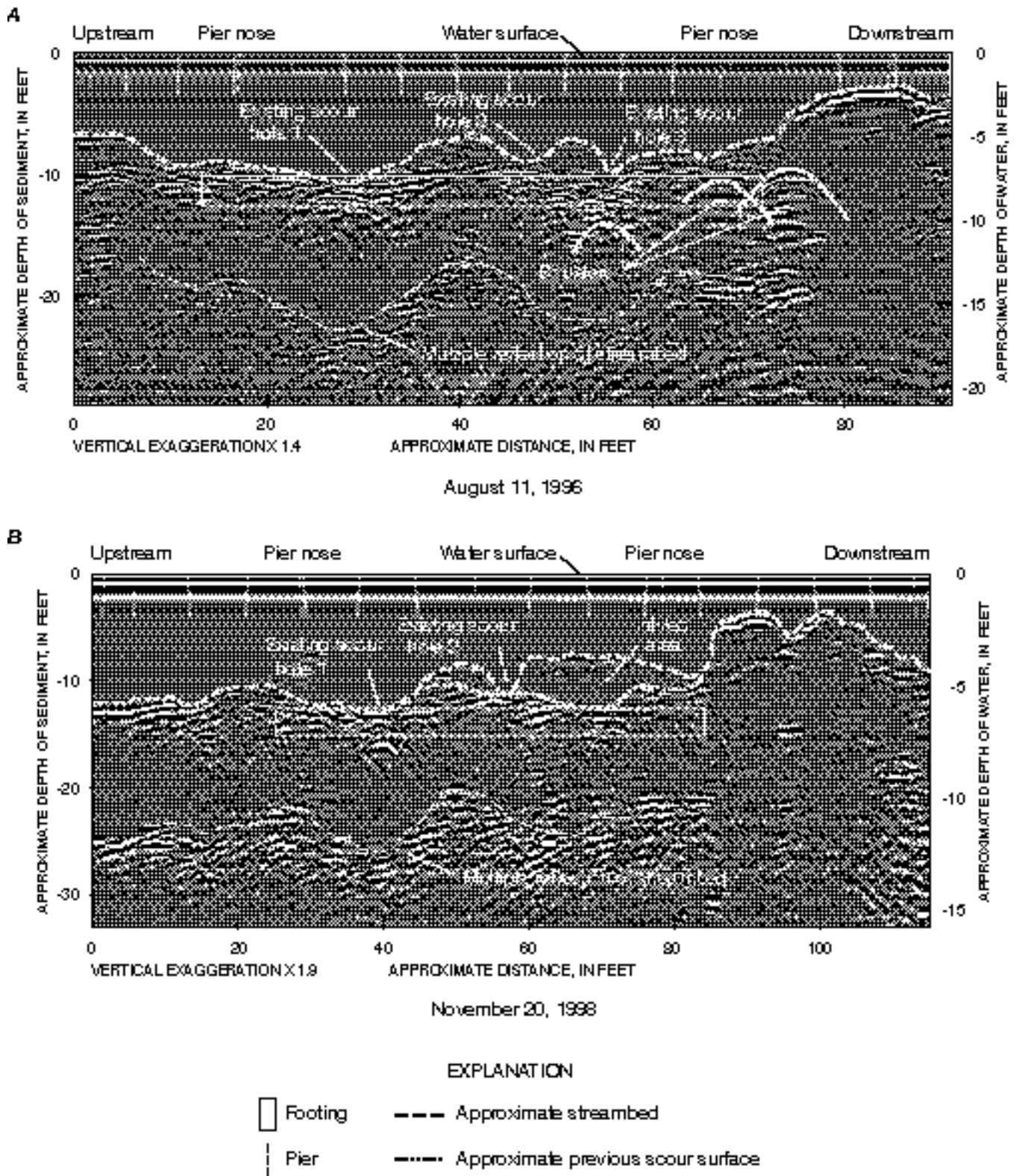


Figure 13. Ground-penetrating-radar profiles of the right-bank pier cross section for (A) 1996 pre-flood and (B) 1998 post-flood data collection, from upstream to downstream, Route 13 over the Souhegan River, Milford, N.H.

SUMMARY AND CONCLUSIONS

Ground-penetrating-radar (GPR) techniques were used to detect pre- and post-flood scour from 1996-98 at bridge sites in New Hampshire in a cooperative study with the New Hampshire Department of Transportation. The 1996 pre-flood GPR cross-section data were collected at 30 bridges. The 1998 post-flood GPR cross-section data were collected at 16 bridges where GPR data were interpretable. Of the post-flood data collected at 16 bridges, 7 sites and 22 profiles were selected for this report. Post-flood data-collection efforts at the bridges were based on the occurrence of a 2-year or greater flood recurrence interval at any of the bridge sites.

The geophysical equipment was operated from a small inflatable boat. The boat was easily maneuvered by an operator wading beside it and guiding it in shallow water. In deep water, an electric trolling motor was used to propel and steer the boat by an operator inside the boat. This method of equipment deployment was fast, safe, and easily transportable from the vehicle to the river's edge by one person. Geophysical record was collected at one bridge per day.

Water depth and streambed materials affected the depth of penetration of the GPR signal. Shallow water (less than 3 ft) had a small affect on signal penetration of streambed materials, whereas deep water (10 ft or greater) attenuated the signal preventing signal penetration beyond 1-2 ft of the streambed. Cobbles and boulder streambeds stopped signal penetration and caused the record to become obscured with multiple inverted triangular reflections.

After data collection, the geophysical record was processed using commercially available software and correlated with data contained in New Hampshire Department of Transportation bridge plans. These data supplemented the geophysical data and aided in the interpretation of depths and locations of footings and geologic materials.

Twenty-two pre- and post-flood cross sections at seven bridge sites are presented and discussed.

Existing 1996 pre-flood data collection scour holes were detected in 14 cross sections. Scour depths ranged from 1 to 3 ft. New, 1998 post-flood data-collection scour holes were detected in seven cross sections. Scour depths ranged from greater than 1 to 4 ft. Infilled scour holes were detected in seven of the post-flood cross sections. Depths of infilling ranged from less than 1 to 4 ft. Field verification of the depth of infilling by means of steel rod and hammer was difficult because of cobble and boulder streambeds or deep water. Previous scour surfaces in streambed materials are identified in 15 cross sections and the depths to these surfaces ranged from 1 ft to 10 ft below the streambed.

Riprap materials or pier footings were identified in all 22 cross sections and calculated record depths generally agree with bridge plans. Pier footings were exposed at two bridge sites and steel pile was exposed at one bridge site. Exposures were verified by field observations.

GPR was found to be an effective tool for detecting existing scour holes, infilled scour holes, and previous scour surfaces at bridge sites. The use of pre- and post-flood GPR surveys was effective in measuring the potential maximum extent of scour that occurred during the intervening period between measurements. If this scour occurred during the highest flow in the intervening period, pre- and post-flood GPR can be effective in maximizing the number of scour measurements at bridges during a flood event. Thus, the use of GPR permits augmentation of scour-data collection that is limited by the number of mobile teams or fixed instrumentation available during floods. GPR also is more versatile than fixed instrumentation mounted on bridge piers because data collection is not confined to the fixed-instrument location. The GPR instrument is mobile and can be positioned anywhere beneath the bridge to collect continuous streambed data in a cross-sectional format. Care must be taken to position the equipment to follow the same traverse paths for comparison of pre- and post-flood measurements.

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